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An Assessment of the Feasibility of Optical Command Post Communication

by Alan R. Downs

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An Assessment of the Feasibility of Optical Command Post Communication

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Abstract

The combat radio used by the fighting units (battalion and smaller) of the U.S. Army is the Single-Channel Ground-To-Airborne Radio System (SINCGARS). This radio system functions effectively, except that the available bandwidth is insufficient to avoid congestion on digital channels. This can result in low throughput and long delays in ordinary tactical situations. This report describes one of a pair of studies that address one possible way to ameliorate this situation (i.e., changing the frequency at which the basic combat radio operates). This study addresses taking advantage of the higher bandwidth available in the optical portion of the electromagnetic spectrum. Three modes of operation are considered (satellite relay stations, direct beam, or terrestrial relay stations). Technological issues, terrain masking, and atmospheric constraints are all considered. Some conclusions and recommendations are also presented.

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1. INTRODUCTION

The objective of the study culminating in this report was to assess and document the feasibility of optical command post communication. The following questions were subsequently considered: Is there a military need? Is there a technical solution? Does the concept make sense?

In performing this study, the first task was to perform a literature search for reports, articles, and Foreign Intelligence Office (FIO) translations of foreign reports and articles. The search limits were made sufficiently wide so that anything pertaining to the subject area could be included. As a result, about 200 abstracts were reviewed for pertinence. Of these, about 30 seemed sufficiently relevant that the entire article was reviewed. Of the 30, eight had sufficient relevance to this study that information contained therein was included in this report. Additional reports were already on hand, so the database for this study is considered to be adequate and representative, if not robust.

Looking at the list of references, one will notice that some of the entries are old (some dating back to the 1960s). This is not surprising in a study of this nature—although actual systems operating at the wavelengths of interest may be a recent development, the environment in which such systems must operate is not. A great deal has been known for decades about such things as atmospheric propagation and terrain obscuration, and it seemed sensible to go to the basic sources and update as needed rather than cite more recent sources and skip some of the background needed for a basic understanding of some highly pertinent information areas.

In any study of this nature, a number of assumptions must be made in order to limit the scope in a meaningful way. In this study, these assumptions are the following:

- The wavelengths of interest are those in the visual and infrared portions of the electromagnetic spectrum (i.e., 0.4–14 μm). The ultraviolet region is excluded because of the severe atmospherics involved. The higher wavelength regions (some define the infrared

to extend to 1,000 μm) are excluded because of the lack of adequate sources and detectors in these regions.

- The transmission ranges of interest are those associated with fighting units (battalion and smaller) and probably, except for air operations, will not exceed 10 km and will most likely average 5 or less. The military is extremely diverse in its communication requirements, and the analysis of all such requirements is well beyond the scope of a quick study. Thus, it was decided to focus primarily on Army operations in a battlefield setting.
- The technical rather than the political possibilities have been explored. The allocation of broadcast bands is a decision that is political in nature (i.e., the decision is out of the hands of the military). There is extreme competition for the optimum channels, and, although allocations have been made and systems are operating throughout the wavelength range of interest, such channel assignment can be changed based on technical, strategic, or financial considerations.
- The option of satellite relay of transmissions is left open (i.e., the possibility is considered in parallel with ground-to-ground and ground-to-air direct links).
- All communication systems to be addressed are line-of-sight systems, which will allow comparisons to be made with the FM single-channel, ground-to-airborne radio system (SINCGARS), which is also a line-of-sight system.

In trying to propagate information from point to point, there are a number of limitations. Some of these limitations (e.g., adequate transmitters and receivers, jamming, robust protocols, and error correction techniques, etc.) are technological in nature. Others (e.g., atmospheric and terrain factors, fading, interference, etc.) are more basic in nature and must be overcome before successful communications are possible. The pertinent factors will be addressed in turn in this section. Since many of these factors are interrelated, the order in which they are addressed is dictated by convenience rather than by priority.

2. CONSIDERATIONS

2.1 Atmospheric Considerations. Before addressing the effect of the atmosphere on communications, it should be noted that those who are expert in radar/radio frequency communications tend to describe the attenuation characteristics of the atmosphere in terms of decibels per kilometer. Those whose background is in optics tend to think in terms of an atmospheric attenuation coefficient (σ) operating over a given distance (r). These terms are related in the following manner:

$$T = \exp(-r\sigma), \text{ and } \text{db/km} = 10 \log_{10}(T)/r.$$

Figure 1 illustrates the way these variables are related.

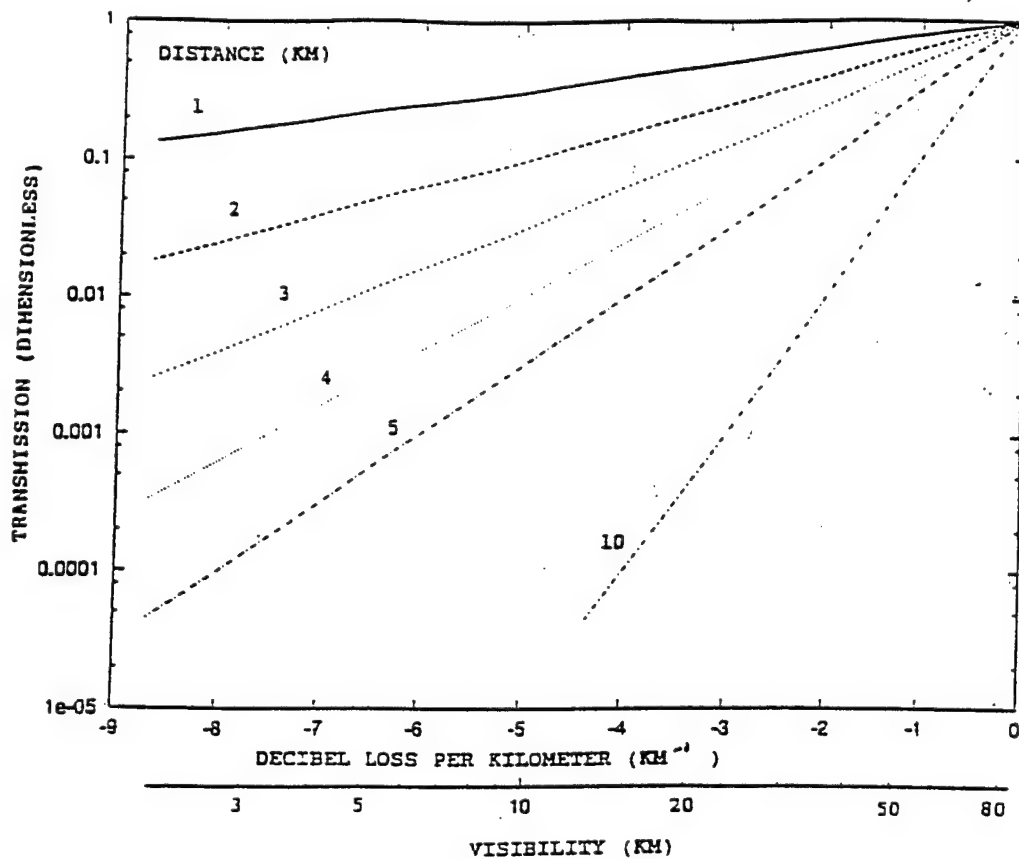


Figure 1. Relationship between optical and radio descriptors.

The second scale on the abscissa is an interpretation aid since the visibility is defined as the distance at which a sufficiently large, black panel can be seen with a 0.5 probability against the horizon sky. It is related to the variables in Figure 2 by the following relationship: $\text{visibility} = 3.912/\sigma$, where 3.912 is the natural logarithm of 50, and 50 is the reciprocal of 0.02 (the nominal contrast threshold of the human eye under daylight conditions) (Middleton 1958).

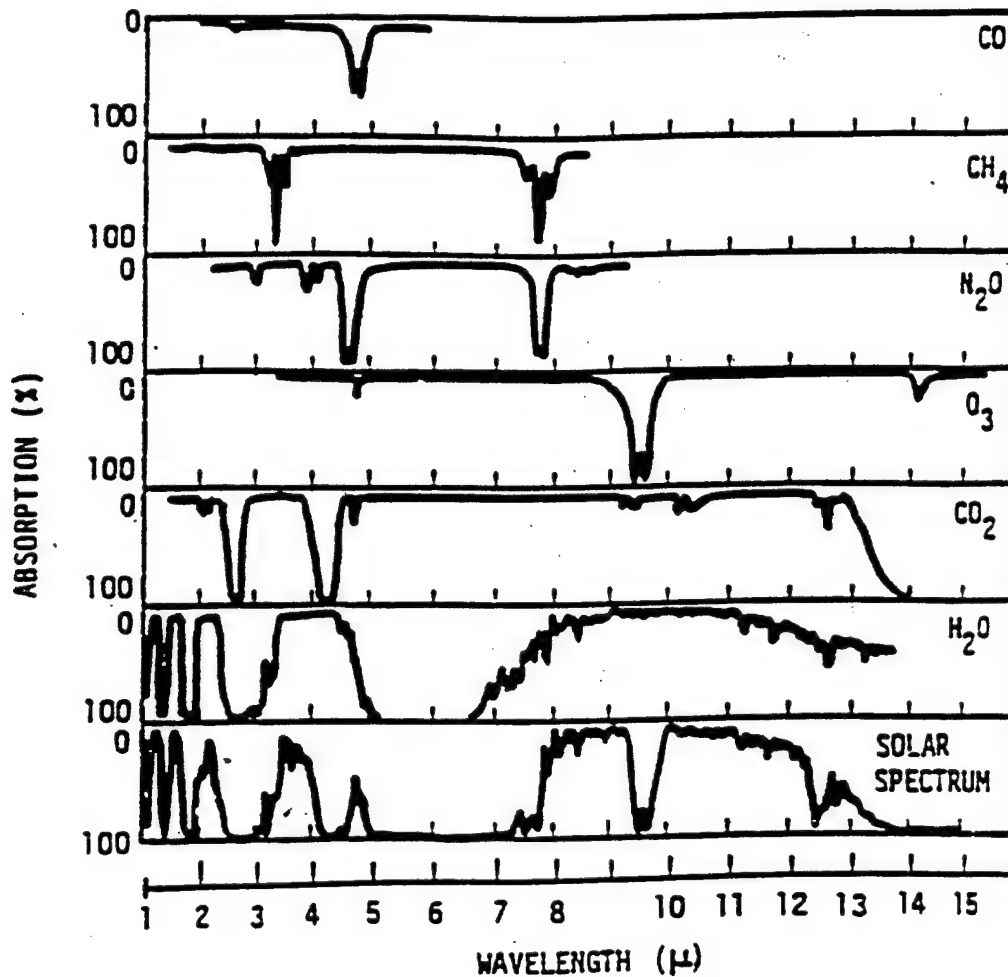


Figure 2. Absorption of optical radiation by atmospheric constituents.

The characteristics of the interaction of optical communication signals with the atmosphere are so dependent on local conditions that trying to develop an overall solution is impossible. As Duffield (1973) states: "The effect of local weather (i.e., rain, fog, clouds, snow, hail, etc.) is so dominant that it governs the realizable path lengths and path reliabilities for millimeter-wave-

(MMW) communication links.” Although this quotation is directed at MMW communication, it applies equally to other parts of the electromagnetic spectrum. The “floor level” (Defense Communication Agency 1979) (i.e., the best that can ever be expected) includes the effects of absorption by carbon dioxide. Even slight amounts of water vapor in the atmosphere can result in absorption at fixed frequencies by that compound. Another gas that presents absorption problems in the infrared is ozone. At high relative humidities, haze and fog can form, thereby giving rise to Rayleigh and Mie scattering. During rain events, the scattering from raindrops can be very strong and is a function of the point-by-point size and concentration of the raindrops. In a battlefield environment, smoke delivered by either side, as well as other atmospheric contaminants (hydrocarbons, dust, blowing sand, etc.), can complicate the situation considerably. This behavior is consistent throughout the electromagnetic spectrum.

The effect of absorption by various atmospheric constituents of radiation in the optical spectrum is shown in Figure 2. As can be seen, the principal absorber of optical radiation is water vapor. The effect of this constituent cannot be predicted with great accuracy since the water vapor concentration at any location below an altitude of 30,000 ft is constantly in a state of flux. The second most important absorber of optical radiation is carbon dioxide. As opposed to water vapor, carbon dioxide distribution in the atmosphere is virtually constant with time and horizontal location, and its density decreases with altitude at the same rate as other gaseous constituents; therefore, its effects can be predicted quite accurately. The effect of ozone can be neglected for practical purposes in surface operations since virtually all atmospheric ozone is found in an atmospheric layer at an altitude of about 80,000 ft. Ozone can be found on the Earth’s surface, particularly in the vicinity of thunderstorms, but such occasional occurrences are not very relevant to this study. Its effects cannot be ignored in ground/satellite communications, however, since the radiation must pass through this layer in both directions. Other minor atmospheric constituents (e.g., CO, CH₄, and N₂O) can present problems, but since their absorption bands are narrow and few, it is easy to select wavelengths outside those specific bands.

The two mechanisms for the scattering of electromagnetic radiation in the atmosphere are the Rayleigh and Mie scattering components. The Rayleigh scattering component results from

scattering by particles smaller than the wavelength of the radiation and is highly selective (i.e., wavelength dependent). It is, in fact, inversely proportional to the fourth power of the wavelength; thus, in the visual spectrum, short-wavelength radiation is scattered much more efficiently than the longer wavelengths, resulting in the sky appearing blue. Rayleigh scattering peaks in those directions perpendicular to the direction of propagation.

The Mie scattering component, on the other hand, results from scattering by particles of the same order of magnitude or larger than the wavelength. The Mie scattering coefficients were determined theoretically in the 19th century, but since they are actually the difference between the sums of very slowly converging infinite series, they were not well known until the advent of the digital computer. Mie scattering, as opposed to Rayleigh scattering, is virtually nonselective (i.e., radiation of all frequencies is scattered with equal efficiency); thus, clouds appear white. Also, as opposed to Rayleigh scattering, there are two peak directions for scattered radiation. The principal peak is in the direction of propagation, and a much smaller peak is in the reverse direction. This phenomenon is responsible for the zodiacal light and gegenschein, respectively, sometimes seen in the night sky and caused by Mie scattering by dust particles in the plane of the solar system (Downs and Reitz 1975).

These factors can interfere with the successful accomplishment of point-to-point communication in several ways. First, the basic scattering and absorption by the atmosphere and its sometimes-present constituents will reduce the signal available at the receiver. Second, the backscatter by the Mie components of the atmosphere will be present at the transmitter; therefore, if the transmitter and receiver are co-located and operate at the same wavelength, the Mie components will appear as noise at the receiver. Third, the forward scatter by Mie components will introduce noise at the receiver of the message recipient. This section will contain some guidelines as to usable wavelengths, but it should be emphasized that there is no one wavelength for which the problems imposed by the atmosphere are minimized; there is just too much normal variation.

Attenuation by atmospheric haze and fog is described in Table 1 (Downs 1976). A couple of points should be made with respect to this table. First, the actual transmission can be calculated from the distance and the attenuation coefficient by using either Figure 1 or the accompanying equations. It is seen that for a nominal distance of 5 km, an attenuation coefficient of 0.01/km results in a transmission of 0.951, and an attenuation coefficient of 38/km results in a transmission of $10^{-82.5}$. Thus, there can be a great difference in transmission for fairly common conditions. Second, in examining the first line in the table (corresponding to a visibility of 0.1 km), it is seen that the attenuation coefficient is both high and independent of wavelength, indicating that an atmosphere characterized by a visibility of 0.1 km has large concentrations of Mie scattering particles that dominate the Rayleigh scatterers and lead to wavelength independence of the scattered radiation. For this reason, fog appears white under a wide variety of lighting conditions.

Table 1. The Effect of Haze and Fog on Optical Scattering Efficiency

Visibility (km)	Wavelength (μm)				
	0.55	1.06	2.3	3.8	10.6
0.1	38.0	38.0	38.0	38.0	38.0
0.2	22.0	22.0	21.0	19.0	17.0
0.5	9.5	9.5	8.7	6.8	4.0
1.0	4.98	4.8	4.4	3.4	1.0
2.0	2.2	2.2	1.9	1.5	0.26
5.0	0.95	0.95	0.85	0.63	0.060
10.0	0.48	0.48	0.42	0.31	0.027
20.0	0.24	0.24	0.21	0.15	0.014
50.0	0.095	0.095	0.083	0.058	0.0086

On the other hand, an examination of the last line of the table (which represents a visibility of 50.0 km) shows that the attenuation coefficient is both low and highly wavelength dependent. Thus, for high visibility conditions, there are so few Mie scatterers that the Rayleigh scatterers, even though they are individually much weaker scatterers, predominate. For this reason, the horizon haze takes on a distinctly blue appearance. As a point of comparison, an atmosphere containing only air molecules and no Mie scatterers is characterized by a visibility of about

300 km (or alternatively, an attenuation coefficient of about 0.013/km in the visual portion of the spectrum).

The other effects that attenuation by water droplets can have on electromagnetic propagation are those of forward and backward scattering. By the nature of Mie scattering, the forward scattering component will dominate the backscatter component for water droplets. The magnitude of both of these effects is shown in Figure 3.

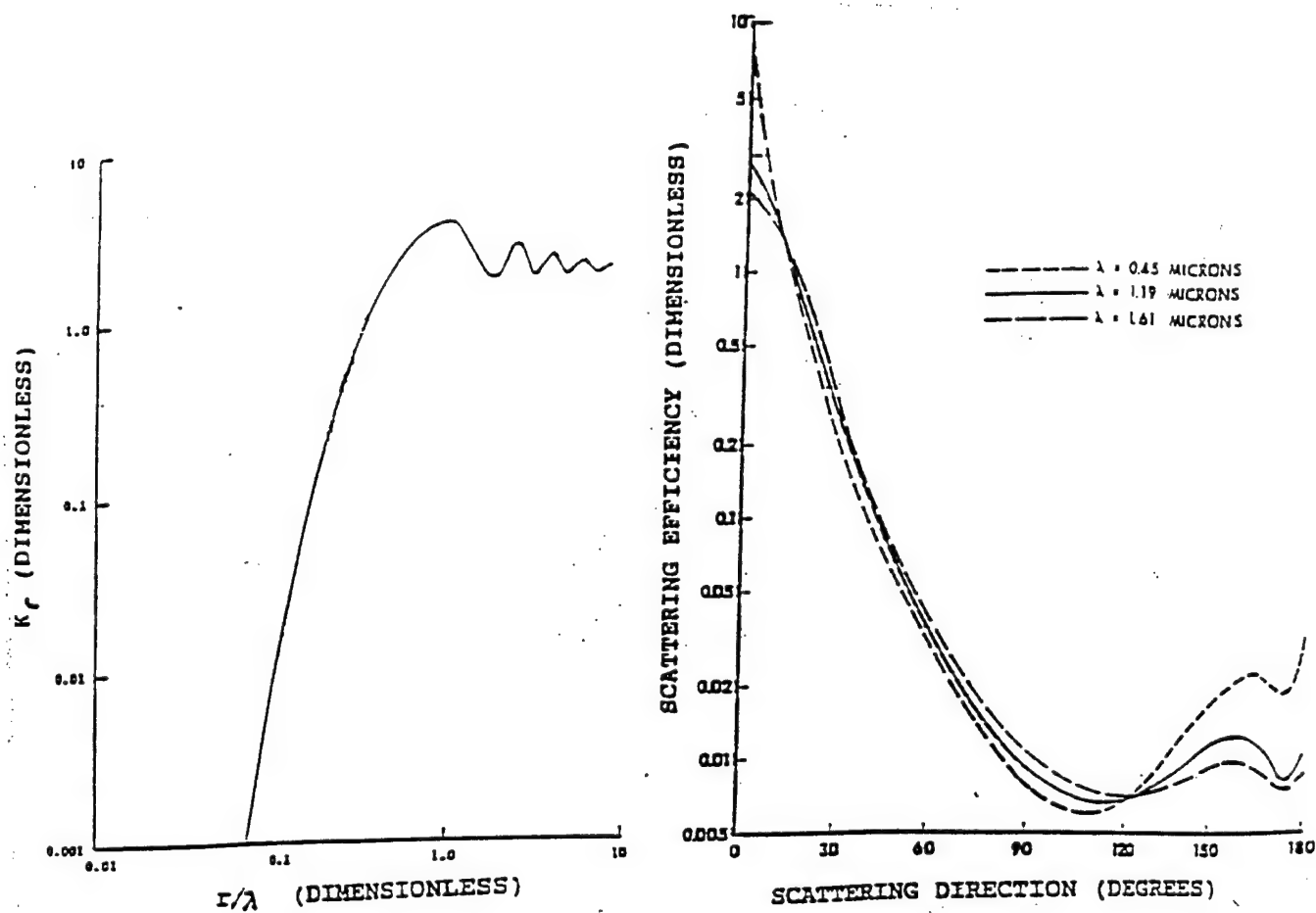


Figure 3. Mie scattering parameters.

The left curve (Downs 1976) shows the scattering area ratio (K_r) for water droplets as a function of droplet size. K_r is the ratio between the area removed from the wavefront by the presence of a droplet and the cross sectional area of the droplet. The energy removed from the wavefront by multiple particles in a monodisperse medium (all droplets are the same size) is proportional to the ordinate of this curve. In a polydisperse medium (the droplets are distributed in size), a similar curve results, but the peaks and valleys are smoothed out. The steep portion of each curve represents the Rayleigh scattering region.

The right curve (Downs 1972) demonstrates the relative scattering efficiency for water droplets at several frequencies in the optical portion of the spectrum. The scattering frequency can be considered relative since the actual values of the ordinate scale pertain to the absolute amount of energy scattered into a steradian and thus are irrelevant in this application. The difference between the three curves is a function of the complex index of refraction of water at the given wavelengths and is unimportant in this study. The abscissa in this graph is the scattering direction as measured from the direction of propagation of the prescattered radiation. The important feature to notice is the ratio between the ordinates for any one curve at the abscissa values of 180° and 0° . The shape of these curves demonstrates that there is a very strong forward scattering lobe and a much smaller backscattering lobe. This phenomenon is very apparent when looking at the moon through a light overcast. The relevance to this study is that the forward scattered radiation will likely take a slightly longer path to reach the receiver. The result is a multipath effect, and this will create interference effects at the receiver.

The effect of rain on propagation of optical radiation is shown in Table 2 (Downs 1976). The key features to notice in this table are the increasing scattering efficiency that results when the rainfall rate is increased, and the near-complete nonselectivity of the medium (i.e., independence of scattering efficiency and wavelength) for all rainfall rates.

It would be negligent to cover the atmospheric effects introduced by haze, fog, and rain, but to ignore a significant contributor to the total atmospheric interference on the battlefield, namely smoke. The adverse effects of some exotic smokes (Reitz 1995) at both optical and radio

Table 2. The Effect of the Rainfall Rate on Optical Scattering Efficiency

Rain Rate (mm/hr)	Wavelength (μm)					V (km)
	0.55	1.06	2.3	3.8	10.6	
1	0.245	0.245	0.246	0.246	0.249	16.0
2	0.376	0.376	0.376	0.377	0.381	10.4
4	0.576	0.576	0.576	0.577	0.582	6.8
8	0.882	0.882	0.882	0.883	0.890	4.4
16	1.35	1.35	1.35	1.35	1.36	2.9
32	2.07	2.07	2.07	2.07	2.07	1.9
64	3.17	3.17	3.17	3.17	3.18	1.2

wavelengths are well-known. Current tactics for smoke usage are primarily defensive (i.e., the use of smoke on or near friendly units to interfere with enemy acquisition or guidance systems deployed against them). There are cases in which smoke can be placed on enemy units (e.g., the use of red phosphorus to disrupt enemy activities while not interfering with friendly electro-optical systems). Such use, however, is outside the scope of the current study. A number of deployment mechanisms have been developed for smokes. These include portable, towed, and vehicle-mounted smoke generators; mortars; field artillery; multiple-launcher rocket systems (MLRS), and air-to-ground rockets. The spatial and temporal properties of intentionally distributed battlefield smokes are very dependent on environmental factors, as well as the method of dissemination. The height of smoke clouds is basically governed by the wind. If there is enough thermal activity to cause the smoke cloud to rise in the first place, it will generally continue to rise until it encounters a thermal layer. The duration of a cloud is dependent on the wind too, but also on the type of smoke employed and the relative humidity, and 60 s is not an uncommon estimate. This time can be extended indefinitely by repeated release of aerosol particulates. The lateral distribution of smoke-cloud particulates is dependent on the wind and the number and spacing of locations at which such clouds are generated.

Currently available smokes are very effective obscurers in the optical portion of the electromagnetic spectrum. That their effects cannot be ignored is borne out by the fact that potential adversaries have invested heavily in this research area and are far ahead of us in fog-oil

generation (which is effective only in the optical region) and closely trail us in the development of the more exotic smokes, some of which are also effective at radio frequencies. The fog-oil smokes affect the visual and infrared wavelengths, sometimes as far as the 8–14 μm region. They are produced by trickling oil on the hot engine manifold. White phosphorus is still in use and is very effective, particularly against imaging systems, for up to 30 s. The effectiveness of this smoke is highly dependent on relative humidity. A more exotic smoke is produced by injecting brass flakes into the vehicle exhaust. The resulting smoke provides good attenuation from the visual through the 14- μm region. Currently, available smokes include some that will provide constant attenuation across the electromagnetic spectrum from about 10 GHz through visual. These smokes can disturb operations at optical wavelengths by scattering from the direct beam, absorption from the beam by graphite particles, backscatter, and reradiation at other frequencies by iron filaments in the smoke. Some current smokes absorb all radiation incident upon them and reradiate in the infrared. Attenuation coefficients for these smokes are functions of concentration, which is in turn a function of the wind characteristics and delivery profiles. Attenuation coefficients can, however, be predicted for tactical situations when the relevant inputs are specified.

Many of the studies referenced in this report address the use of satellite relay stations. In order to place such studies in the needed perspective, it seems desirable to introduce the concept of slant-path atmospherics. The basic references for this analysis (Downs 1972; Downs, Joel, and Yunker 1973) were limited to the optical region of the electromagnetic spectrum, but the formulations and analysis provided have general application and, thus, are pertinent to the radio spectrum as well.

The basic equation for the scattering of electromagnetic radiation passing through a medium is

$$T = \exp(-r\sigma),$$

where T is the transmission of the medium, r is the distance traveled in the medium, and σ , with the units of inverse kilometers, is the attenuation or scattering coefficient of the medium. Since σ

is composed of both Rayleigh and Mie scattering components, it is , at any single wavelength, the sum of the Rayleigh and Mie scattering coefficients. Each of these coefficients is independently wavelength (frequency) dependent, so determining the scattering from a beam that contains a number of frequencies must be done by summing the scattering coefficients over a set of sufficiently narrow wavelengths when the single-wavelength coefficients are weighted by the intensity of the radiation at each wavelength (frequency). If σ is independent of r , this procedure is relatively straightforward. The problem with this assumption is that σ is a function of altitude. This assumption, therefore, only stands a chance of being true to within reasonable limits when the propagation path is horizontal.

If the scattering particles were distributed evenly with altitude to the "top" of the atmosphere (height = h), the following slant-path formulation must be used. If the propagation path is inclined to the horizon by an angle θ , the foregoing equation for the transmission to a distance r is

$$T = \exp (-r\sigma) \quad r \leq h/\sin (\theta)$$

$$T = \exp (-h\sigma/\sin \theta) \quad r > h/\sin (\theta).$$

This equation, which neglects the effect of the Earth's curvature, would be true if the scattering particles were distributed evenly with altitude to the top of the atmosphere and then stopped sharply. In reality, the concentration of the scattering particles decreases with altitude. In addition, the concentration of each type of scattering particle varies with altitude in a different manner.

At this point, it seems reasonable to introduce a definition. The scale height of a particular atmospheric constituent is that horizontal distance over which the total amount of a given constituent in the path is the same as the amount of the same constituent in a vertical path that extends from zero to infinity. The scale height is thus seen to be a function of the particular type of constituent of interest. The referenced reports describe the development of a mathematical model to describe the slant-path attenuation by the atmosphere and various constituents. No

model can be fully predictive in this regard since the attenuation coefficient (σ) is generally a strong function of position and is not known point-by-point, even for horizontal paths. When a slant path is considered, the likelihood of knowing the concentration of scattering elements point-by-point is zero. The scale height is a prediction of the manner in which the concentration of relevant scattering elements decreases with altitude based on ground-level observable variables. Several examples of the manner in which the attenuation coefficient varies with altitude is shown in Figure 4.

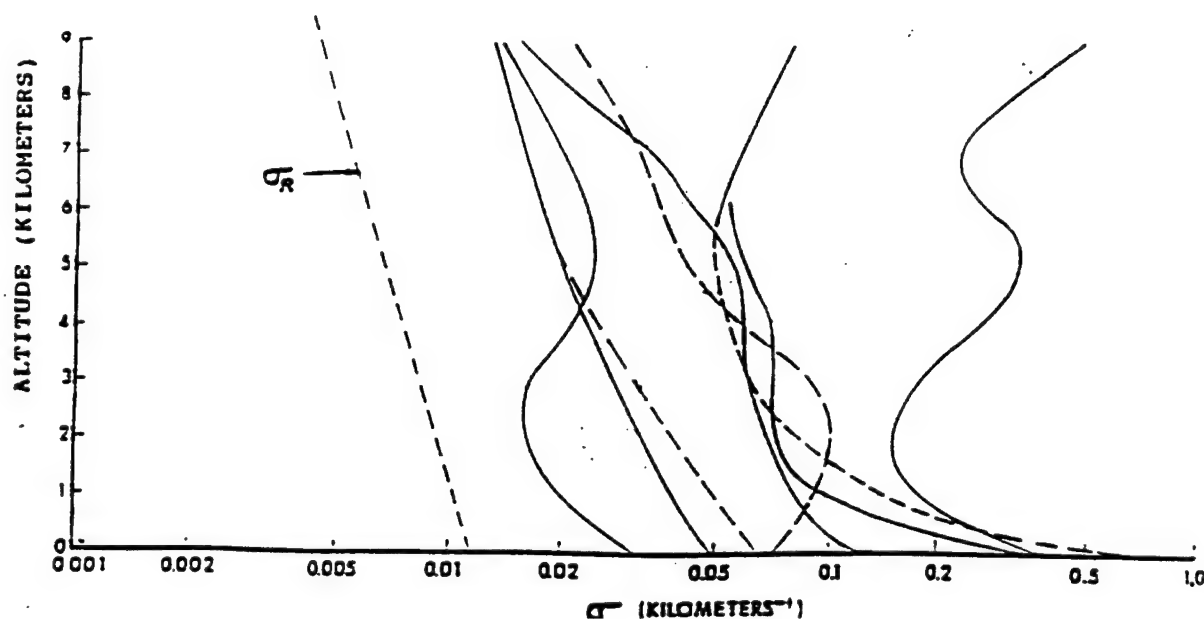


Figure 4. Altitude dependence of Rayleigh and Mie scattering coefficients.

The abscissa on this figure is the sum of the Rayleigh and Mie scattering coefficients. The straight line on the left is the Rayleigh coefficient alone. Such a straight line indicates an exponential rate of decrease with altitude. About all that can be said of the other lines is, in general, that above an altitude of about 3 km, the concentration of the Mie scattering particles decreases with altitude. For a couple of high- σ curves, even this assumption is seen to be in error.

It is obvious from the figure that no simple model can predict the attenuation coefficient as a function of altitude with high accuracy based on ground-level observable variables. It is possible,

however, to obtain an estimate if one accepts the fact that in unusual cases, of which two are shown in Figure 4, sizable errors will result. For full details, the reader must consult the basic study (Downs 1972), but the methodology entails integration along a slant path wherein the scale height for Rayleigh scatterers is 8.0 km, for water vapor is 5.7 km, and for Mie scatterers when the ground-level visibility is greater than $G(\lambda)$ is 4.1 km. $G(\lambda)$ is generally a strong function of wavelength, and typically varies between 10 and 30 km. When the visibility is less than $G(\lambda)$, the situation is quite complicated and entails integrating along two paths; one of which has a scale height of 4.1 km and the other having a scale height that is a complicated function of the ground-level visibility.

The amount of detail in the described model is not necessary for this study, however, since slant-path reliabilities are given in the referenced literature. Most of these reliabilities are determined based on similar models or on a limited-size data set, and the previous analysis is provided to allow the reader to estimate the uncertainties involved in such predictions. Another effect that the atmosphere can have at optical wavelengths is scintillation. Scintillation is caused by the nonuniform temperature of the atmosphere in a localized area, resulting in atmospheric globules varying in size from millimeters to centimeters. This phenomenon is mostly found in hot and dry conditions. Depending on the size of the globules with respect to the diameter of the beam, they can cause the beam to break up or can refract (steer) the beam as a whole.

A test of the magnitude of this effect was made (Korevaar and Schuster 1994) at 8.852 μm using a communications laser with a divergence of 2 μrad and a retro reflector located at different distances at sea level elevations. It was found that with the retro reflector located at a distance of 8 mi (12.9 km), the signal would fade in and out. When the retro reflector was located at a distance of 4 mi (6.4 km), a high-quality signal resulted. The magnitude of the observed fading was typically four orders of magnitude and occurred over time scales of a few tenths of a second.

2.2 Terrain Considerations. The effect of terrain on signal propagation has been addressed in a large number of studies of which only a sampling will be covered here. Most of the line-of-sight/terrain blocking studies uncovered in this study were based on the radio spectrum, but since

the systems of interest are all line-of-sight, this fact is irrelevant to this study. As Brennan (1987) states, "The effect of varying terrain roughness in determining if a communications link is good is probably the most important factor to consider. In general, the rougher the terrain, the fewer the number of good links a network will have." This effect can result in the interruption of tactical operations and can prevent effective command and control. The referenced study used a computer model, the Ground Network Communication Model (GNCM), developed jointly by the U.S. Army Communications and Electronics Command (CECOM) and the Department of Commerce, to look into this problem at a wavelength of 1.8 GHz. This model was used to deploy radios in an actual geographic area based on elevation data taken from digitized maps provided by the Defense Mapping Agency. The GNCM was then used to calculate, link-by-link, the path loss for all possible links within this array.

In the actual study, 51 radios operating at 1.8 GHz were deployed over a 40-km \times 40-km grid. The radios were then moved in steps of 200 m in random directions and the situation reevaluated. This process was repeated 250 times. Statistics on which links could communicate at each configuration were collected. This process was repeated in five different types of terrain. Since the radio deployment was done only under good weather conditions, the results reflect the effects of terrain alone.

Although no definitive answers could be obtained, the following conclusions could be drawn:

- In all types of terrain, signal connectivity losses occur.
- Surprisingly, greater signal connectivity losses occur in smooth terrain.
- As the experiment progresses, there is a tendency to form clusters of intercommunicating radios that are isolated from all radios outside the cluster. Again, this effect is most severe in smooth terrain.

Finally, another study (Johns Hopkins Applied Physics Laboratory 1960) analyzed the mean tank-engagement ranges in Europe during World War II. This study is pertinent since the tank-engagement tactics of both sides were the same—"When you see an enemy tank . . . shoot." These tactics made sense at the time since remaining motionless until the enemy was at a closer range had been demonstrated to be a losing proposition. There was too much of a chance that the enemy would see the motionless tank and get off the first shot. The probability of a kill with the first shot was low; however, this tactic allowed corrections to be made before the opposing tank could get off its first shot, and the probability of a kill with the second shot, even at extreme range, was too great to be discounted. Based on these tactics, the range at which the tanks were engaged is also a measure of the intervisibility distance in that area. Since these engagement ranges were known, statistics could be generated on the intervisibility distance from the engagement reports. It should be noted that the distances involved were, in general, true-sample intervisibility distances since conditions other than chance encounter (e.g., tanks in defilade or in preselected positions) were not considered in the study. The basic conclusion of this study was that the engagement ranges could be represented by a Pearson III distribution with a mean of 728 m and a variance of 310 m. The two-parameter Pearson III distribution reduces to a Gamma distribution.

The Gamma distribution with the mean and variance as given is shown in Figure 5. The mean of this distribution is indicated by the vertical line. It can be seen that the most likely intervisibility distance is less than the mean, and around 600 m. It is also apparent that the likelihood of an intervisibility distance in excess of 2 km in European terrain under the described conditions is small.

2.3 Other Considerations. Optical links exhibit problems that result from their line-of-sight nature. Natural and man-made obstacles can seriously degrade communications in both the ground-ground and air-ground modes; however, satellite links can overcome most of these limitations. Some advantages offered by satellite/optical communication links include (Korevaar and Schuster 1994; Sundaram 1988; and Casey et al. 1991):

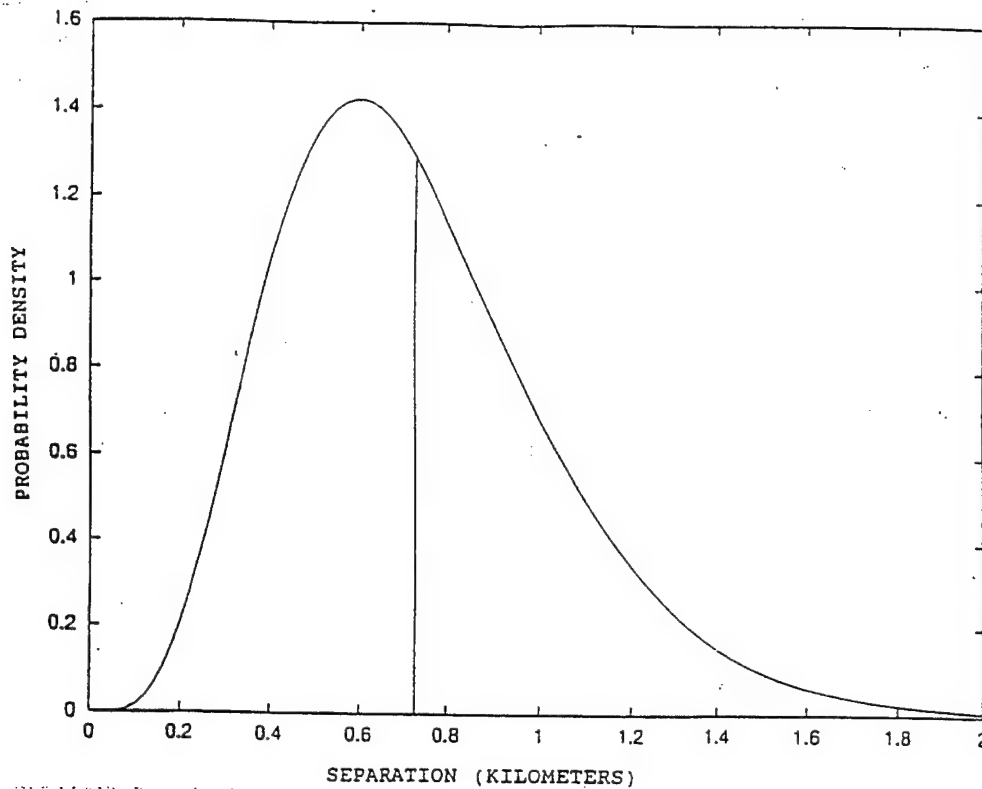


Figure 5. Gamma distribution with mean of 728 m and variance of 310 m.

- They are extremely reliable.
- The network can be reconfigured rapidly and easily.
- They are not affected by distance, terrain, or other obstacles.
- Available bandwidth is extremely high (i.e., exceeding one GBPS).
- Data rates are limited only by the satellite's transmitter output power and the sensitivity of the ground receiver.
- Large numbers of users can be accommodated.

- Achievable size, weight, and power compare very favorably over comparable systems operating at radio frequencies.
- The state of the key technologies (e.g., lasers, detectors, and filters) is highly advanced.
- Potential systems are low-risk and could be developed in minimum time.

One reason that optical communications are being studied so carefully is that the beam divergence is so small. As an example, at a radio frequency of 60 GHz, a 3-m aperture antenna would produce a beam with a divergence of 2.7 mrad. On the other hand, a laser operating at 0.81 μm and a 15-cm aperture would produce a beam with a divergence of 9 mrad, a factor of 300 lower (Korevaar 1994).

The U.S. Air Force has identified laser communications as a technology worth pursuing for several air-to-air communications applications (Casey et al. 1991). The very narrow beams used in this technology and the very low sidelobes provide considerable protection against hostile monitoring/jamming of communication links that employ such beams. The other side of the coin, however, is that the narrower the beam, the more difficult it is to acquire by a legitimate recipient of information to be sent over the beam. In a fluid battlefield situation, at least one of the communicating units will be moving frequently, and after each move, the communication link must be reestablished. The process of establishing a communication link entails one unit sweeping his transmitter throughout the solid angle of uncertainty while the other unit's field of view (FOV) is fixed. If an acquisition does not take place, the receiver shifts his FOV slightly and the process is repeated until acquisition occurs. If the beam that was employed was the direct laser beam, the search times would be so great that this system would be of no use. Instead, the beam is spread. The spreading cannot be too great since the signal-to-noise ratio increases with beam-solid angle. Even when spread beams are employed, the search times can be long as exemplified in Figure 6.

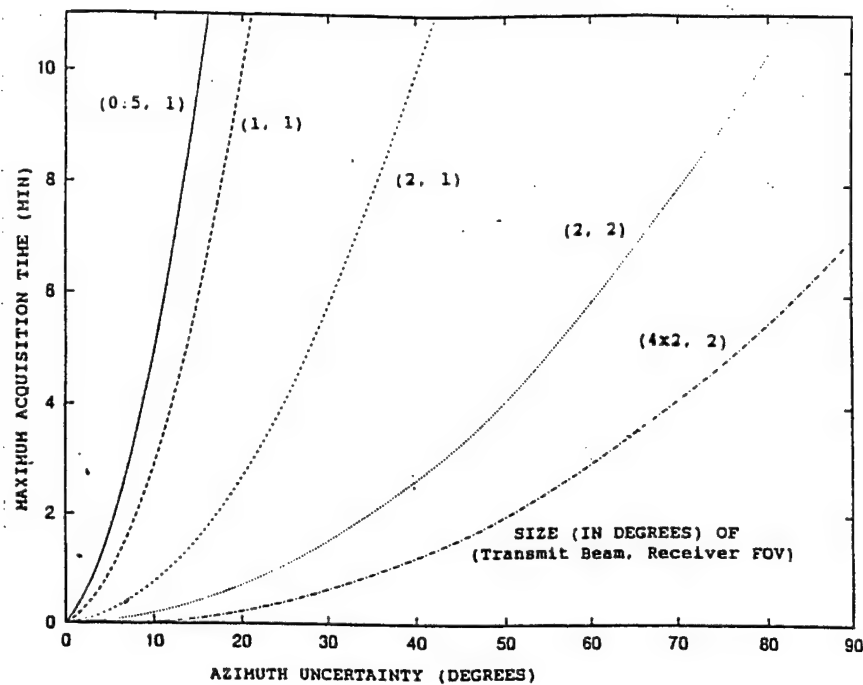


Figure 6. Acquisition time as a function of azimuth uncertainty and transmitter/receiver characteristics.

Another factor of importance in assessing the technical parameters of a system is the bit error rate. Little was found on the subject in the reviewed literature, but a data point was given in Korevaar (1994). An estimate of 10^{-6} was provided for one system operating at $0.81 \mu\text{m}$ with a data rate of 1.08 GHz and a signal-to-noise ratio of 6.0. This value will be assumed to be representative of the optical spectrum.

One of the key factors to consider in analyzing whether optical communication systems have a useful place in the Army inventory is the data-transmission rates achievable in a battlefield environment. The Air Force has recently funded several technology thrusts through the U.S. Army Space and Strategic Defense Command. One result (Korevaar 1994) has been some extremely high data rates compared to what the Army uses now. Data rates of 1.08 GB/s have been achieved and data rates of 270 MB/s are expected to be routinely achievable for the aircraft/satellite communications role. Although the Army will be operating in a more deleterious environment, data rates much higher than currently used should be easy to achieve in the near future.

A key component that must be present in any laser communication system is a narrow bandpass filter that is inserted in the receiver prior to the detector (Casey et al. 1991). The purpose of such a filter is to remove background radiation that would otherwise contribute to noise in the system. A recent outgrowth of submarine laser-communication technologies has been the development of several types of filters, each combining a narrow bandpass with a wide acceptance angle. The following are the filter types:

- **Birefringent Filter:** This filter uses polarization elements to screen out all wavelengths except the narrow bandpass. One such filter usable at a wavelength of $0.532\ \mu\text{m}$ has a transmission of 35% over a passband of $0.00033\ \mu\text{m}$. The acceptance window for this filter is greater than 45° . The bandpass and center wavelength of this filter can be tuned for use at any visible and near-infrared wavelength.
- **Atomic Resonance Filter:** This filter is chemically complex and relies on atomic resonance. It has discrete center wavelengths, and the bandpass is less than $0.00001\ \mu\text{m}$ with an acceptance angle that is near hemispherical. This filter is also known as an atomic line filter (ALF).
- **Cadmium Sulfide (CDS) Dispersive Birefringent Filter:** This filter operates with the neodymium-doped YAG laser ($0.532\ \mu\text{m}$) and is a zinc-doped version ($0.486\ \mu\text{m}$). The acceptance angle is nearly hemispherical with a transmittance of about 20%. A passband of $0.0001\ \mu\text{m}$ is achievable.

Another optical system component that is extremely important in an optical communication system is the detector that is used in the system. A sample of current detectors is presented in Figure 7 (Rogatto 1993). The ordinate on this figure is not given dimensions, since for the dimensions to be meaningful, considerable detector theory would have to be given, and this would be outside the scope of this study. Here, it should be sufficient to say that detectivity, usually given the symbol D^* , is the signal-to-noise ratio normalized to photon energy, optical area, and system power bandwidth. It has units of $\text{cm} - \text{Hz}^{1/2}/\text{W}$. The key feature to notice in this figure

is that quality detectors are available throughout the spectral region of interest and beyond. Some of these detectors can operate at ambient temperature, whereas some need to be cooled. Cooling a detector in the field to the temperature of 77° K (liquid nitrogen) is no big problem. The employment of detectors that need to be reduced to 3° or 4° K (liquid helium) would present considerable logistics problems, and therefore would be unacceptable. At shorter wavelengths, other detector types (e.g., avalanche photodiodes) are available off-the-shelf. The response time of some of these detectors is very short, in some cases approaching a picosecond (10^{-12} s).

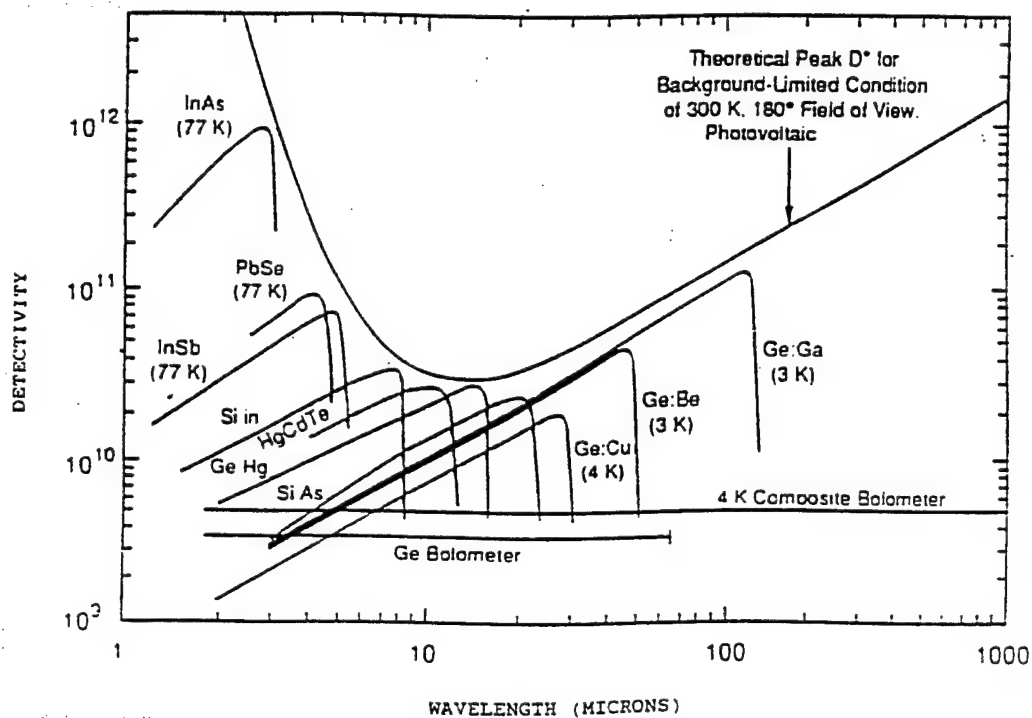


Figure 7. Detectivities of selected infrared detectors.

3. CONCLUSIONS AND RECOMMENDATIONS

The objective of this study, as stated in the introduction, is to perform an analysis of the feasibility of optical command post communications. In developing this report, the most sensible way of approaching this objective was considered to be by answering the following questions:

- What regions of the optical spectrum (0.4–14 μm) are potential regions for future tactical communications systems?
- Which of these regions offers the most promise for viable communications in the reasonably near future (i.e., based on today's technology)?
- What tactic of employment makes the most sense (i.e., is likely to provide the best results)?
- How does this selected frequency/tactic compare with the current system used for battlefield communications?

So far in this report, a lot of loosely connected information has been presented for various wavelength bands. Some of the information has been concrete and well-defined, while other parts have been primarily subjective. There is, however, sufficient information available from which to draw some definite conclusions.

The most desirable way to proceed at this point is to provide some basic information about the system that is currently used to provide battlefield communications. This system is the SINCGARS. Some of the pertinent characteristics of SINCGARS are provided in Table 3 (Headquarters, Department of the Army 1992; Alexe, DiPatri, and Meiner 1995; and Fox 1991). In the same table are presented nominal characteristics of a potential candidate for a competing optical communication system.

From Table 3, it is seen that except for acquisition time, the optical communication system will outperform the current SINCGARS system in every pertinent way with no compensating drawbacks. The acquisition time, however, is quite pertinent to the way that the Army performs its mission. If a command post wanted to make contact with a moving vehicle, a delay of seconds to minutes would be intolerable since responsiveness on the battlefield is a critical element. If we assume that the acquisition time can be reduced sufficiently to meet the needs of the military tacticians, one must also contend with the weather and terrain.

Table 3. Pertinent Characteristics of SINCGARS and a Generic Competing Optical Communications System

Characteristic	SINCGARS	Optical
Operating Band	30–88 MHz	0.4–14 μm
Number of Channels	2,320	Almost Unlimited
Data Rate	= 16 KM/s	1 GB/s
Countermeasurability	Significant	Insignificant
Bit Error Rate	10^{-6}	10^{-6}
$T_{t\text{ km}}$ (Clear Air)	0.463	0.350
$T_{t\text{ km}}$ (Moderate Rain)	0.112	0.00184
Acquisition Time	Very Short	s/min

If it is assumed that the technical parameters are adequate, and that the feasibility of an optical command post is dependent on environmental parameters, the following analysis must be considered. The Air Force is seriously pursuing the concept of air-to-air optical communication based on its superior technical performance. This is wise, based on where the Air Force operates. In air-to-air communications, the communication beam is above terrestrial barriers and does not generally have to contend with clouds, rain, haze, fog, etc. However, Army ground-to-ground or ground-to-air operations are not as fortunate. If an optical command post is to be a realistic goal for the Army, it must operate in one of the following three ways: satellite relay stations, direct beam, or terrestrial relay stations. These operational factors will be considered in turn.

If a satellite relay station is used, the following procedure must be employed. If a command post wishes to send information to a mobile vehicle and receive a reply, it first must send the information to a communication satellite. Since the satellite's location is fairly accurately known, the acquisition time is relatively small. The satellite must then search for the mobile vehicle and establish contact. This is more time-consuming since the laser footprint is small. It would still be

much shorter, however, than the ground-to-ground case since the mobile vehicle is known to be within a given distance of the command post. Once contact is established, the satellite can routinely send the information to the vehicle, receive a reply, and relay the reply to the command post. Although seemingly routine, the drawback is that the two-way transmission and reply must pass through the deleterious effects of the near-earth atmosphere, as well as any clouds that intersect the paths. To determine the effect of the atmosphere on the transmission of optical radiation, Tables 1 and 2 and the techniques described in section 2.1 can be applied. The result is shown in Table 4.

Table 4. Atmospheric Slant Path Transmission as a Function of Environmental Parameters

λ (μm) ->	Satellite Elevation Angle ($^{\circ}$)					
	60		45		30	
	0.55	10.6	0.55	10.6	0.55	10.6
V (km)						
20	2.06×10^{-01}	9.12×10^{-01}	1.44×10^{-01}	8.73×10^{-01}	6.45×10^{-02}	8.52×10^{-01}
10	4.23×10^{-02}	8.37×10^{-01}	2.08×10^{-02}	8.04×10^{-01}	4.18×10^{-03}	7.35×10^{-01}
5	1.91×10^{-03}	6.75×10^{-01}	4.67×10^{-04}	6.18×10^{-01}	1.95×10^{-05}	5.07×10^{-01}
2	1.07×10^{-05}	4.45×10^{-02}	8.21×10^{-107}	1.91×10^{-01}	2.48×10^{-09}	9.63×10^{-02}
1	2.06×10^{-10}	1.76×10^{-02}	4.75×10^{-11}	7.09×10^{-03}	2.52×10^{-15}	9.12×10^{-04}

Table 4 illustrates several points quite clearly. First the nonlinear character of the transmission is readily apparent (i.e., if the visibility is halved, the transmission is not halved, but rather squared). Second, the atmosphere is much more transparent at 10.6 μm than it is at 0.55 μm . Third, if there is little impediment to seeing (high-visibility or low-rainfall rate) the transmissions are high at both wavelengths. It must be remembered, however, that when haze and/or fog is present there will be forward scattering sufficient to cause interference at the receiver, and the presence of any clouds in the battlefield area will drastically affect optical propagation. Finally, it should be noted that in the cases of low-visibility or high-rainfall rate, the transmission, even at 10.6 μm , is too low to make a laser communication system viable.

If a direct beam system is postulated, clouds will not generally be a concern. However, the transmissions can be even lower than is the case with a satellite relay. For example, if the command post/mobile vehicle distance is 5 km and the visibility is 2 km, the transmission along the direct link is 1.67×10^{-5} and 3.67×10^{-1} at 0.55 and 10.6 μm , respectively. The corresponding transmissions using a satellite relay with an elevation angle of 45° , are 8.21×10^{-7} and 1.91×10^{-1} , respectively. In addition, the effect of terrain is very deleterious. A glance at Figure 5 will show the problem. If the command post is placed in a location that is favorable (e.g., a hilltop), the terrain effects are much less restrictive, but there is a tremendous impact on survivability. A standard tactic of any potential adversary would be to bring heavy-artillery fire upon such areas that they do not want to be occupied. In addition, even if a line-of-sight did exist, the acquisition time is likely to be unacceptably high.

Using a terrestrial relay station is probably the best choice among the three available options. Clouds will generally not present a problem. As the distances between the command post and a relay station, between relay stations, and between the final relay station and the mobile vehicle are all likely to be less than that between the command post and the mobile vehicle, the transmission along any leg is less likely to be corrupted and more likely to be recoverable if corrupted than in the case of direct transmission. Propagating the information along several legs, however, will reduce the likelihood of successful transmission for the entire route since it is equal to the product of the probabilities of success along each leg. Also, unless the final relay station is situated in a favorable position, its chances of survival are small. This use of a fixed relay station can operate counter to the high degree of mobility required of modern combat units.

Again, in this case, the acquisition time is likely to be unacceptably high. This report, presents information that leads to the following conclusions:

- The technology needed to develop an optical command post is well advanced, and any such project can be considered low-risk.

- There are sizable benefits (e.g., data rates, number of available channels, countermeasure avoidance) that would enhance the desirability of such a command post.
- The environmental parameters during favorable conditions are such that an optical command post could function as needed.
- There is no indication that such a command post could function, even under favorable conditions, any better than current command posts using SINCGARS.
- Under unfavorable conditions, the environmental parameters are so severe that an optical command presents an unfavorable system at this time.

It is felt that if potential adversaries could be persuaded to change their tactics (e.g., restrict their operation to clear, cloudless days, fight only in gentle, rolling, nondesert terrain, and stop firing artillery at favorable command post locations) an excellent optical command post could be designed and developed in a very short time and at reasonably low cost. Since this is an unlikely scenario, it is felt that optical command post communications is not a goal worth pursuing at the present time. Since certain technological advances could invalidate these conclusions, however, research should continue in various areas (e.g., reducing acquisition time, reconstruction of corrupted signals, and increasing modulation rates).

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